

Final report, Contract NAG5-9040

Investigation Title: Validation and improvement of SRTM performance over rugged terrain

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Recent progress

We have previously reported work related to basic technique development in phase unwrapping and generation of digital elevation models. In the final year of this work we have applied our technique work to the improvement of DEM's produced by SRTM. In particular, we have developed a rigorous mathematical algorithm and means to fill in missing data over rough terrain from other data sets.

We illustrate this method by using a higher resolution, but globally less accurate, DEM produced by the TOPSAR airborne instrument over the Galapagos Islands to augment the SRTM data set in this area. We combine this data set with SRTM to use each set to fill in holes left over by the other imaging system. The infilling is done by first interpolating each data set using a prediction error filter that reproduces the same statistical characterization as exhibited by the entire data set within the interpolated region. After this procedure is implemented on each data set, the two are combined on a point by point basis with weights that reflect the accuracy of each data point in its original image.

In areas that are better covered by SRTM, TOPSAR data are weighted down but still retain TOPSAR statistics. The reverse is true for regions better covered by TOPSAR. The resulting DEM passes statistical tests and appears quite feasible to the eye, but as this DEM is the best available for the region we cannot fully verify its accuracy. Spot checks with GPS points show that locally the technique results in a more comprehensive and accurate map than either data set alone.

The results are described in a paper submitted to IGARSS-2004, which is attached to give a complete description of the method and its results. The abstract for this work follows:

"We present a method for correcting large-scale artifacts and for interpolating regions of missing data in TOPSAR DEMs. Artifacts are eliminated by subtracting the difference between the TOPSAR DEM and the SRTM DEM. The inversion method using a prediction error (PE) filter was used to interpolate the missing data holes so that the

interpolated regions would have the same spectral content as the originally valid regions of the TOPSAR DEM. Along with the PE filter, the SRTM DEM for the same area is used as another constraint in the interpolation. We used cross-validation to obtain the optimal weighting of the PE filter and SRTM DEM constraints.”

In previous years, we have been able, using network flow techniques, to unwrap very large (100 km x 800 km) ERS interferograms, which were illustrated in large scale maps of Alaska. We also modified the statistical description of the network flow paths to allow the methods to be used for deformation interferograms, and applied this version to unwrapping the Hector Mine interferogram. The method has proved exceptionally stable and accurate, and is described in detail in a Ph. D. thesis by Curtis Chen.

Results presented in several journal articles as listed below and in Chen’s thesis, as listed in his abstract:

“Two-dimensional phase unwrapping is a key step, and often the most significant error source, in the analysis of synthetic-aperture-radar interferograms. In the interferometric technique, very accurate measurements of the Earth’s topography or its surface deformation are derived from radar-image phase data. Phase, however, is defined only modulo 2π rad, so a resulting 2-D array of measurements is wrapped with respect to some modulus or ambiguity. These data must be unwrapped to provide meaningful information. For this purpose, we introduce a new, nonlinear constrained-optimization approach in which i) defined cost functions map particular unwrapped solutions to scalar costs and ii) a solver routine computes minimum-cost solutions. Previous efforts have focused mainly on simple cost functions that have yielded efficient—but not necessarily accurate—algorithms. These inaccuracies seriously degrade the effectiveness of the interferometric technique and can preclude useful geophysical interpretation of the data. We propose a new set of nonconvex, statistically based cost functions through which we treat phase unwrapping as a maximum a posteriori probability estimation problem. That is, we derive approximate, application-specific statistical models for the problem variables. Based on these models, we cast phase unwrapping as an optimization problem whose objective is to find the most physically probable unwrapped solution given the observable quantities: wrapped phase, image intensity, and interferogram coherence. We prove that the resulting problem is NP-hard, and we develop nonlinear network-flow solver techniques for approximating solutions to this problem. Extending our statistical framework and network methods, we also present a tiling heuristic for applying our algorithm to large data sets. Performance tests on topographic and deformation data acquired by the ERS-1 and ERS-2 satellites suggest that our algorithm yields superior accuracy and competitive efficiency as compared to other existing algorithms.”

We have in addition published three journal articles and several conference presentations describing various aspects of this problem.

This study has produced one Ph.D. thesis (Curtis Chen, now at JPL) and will be the basis of several chapters in Sang-Ho Yun’s Ph.D. dissertation.

Published journal papers

Yun, S-H., J. Ji, and H. Zebker, TOPSAR DEM Interpolation Using a Prediction Error Filter and SRTM DEMs, in preparation, 2004.

Curtis W. Chen and Howard A. Zebker, "Tiling methods for network-flow approaches to InSAR phase unwrapping," Journal of the Optical Society of America A, March 2002.

Curtis W. Chen and Howard A. Zebker, "Network approaches to two-dimensional phase unwrapping: intractability and two new algorithms," Journal of the Optical Society of America A, Vol. 17, No. 3, pp. 401-414 (March 2000).

Chen, C.W.; Zebker, H.A., Two -dimensional phase unwrapping with use of statistical models for cost functions in nonlinear optimization, Journal of the Optical Society of America A (Optics, Image Science and Vision), Vol.18, No.2, p.338-51, Feb. 2001.

Chen, C.W., and H.A. Zebker, Comparison of InSAR Phase Unwrapping Techniques for DEM Generation, American Geophysical Union 2000 Fall Meeting, December 15-19, 2000, San Francisco, California. Published: EOS, Transactions, American Geophysical Union, Vol. 81, No. 48, p. F313, November 28, 2000.

Conference presentations

Chen, C.W., and H.A. Zebker, Comparison of InSAR Phase Unwrapping Techniques for DEM Generation, American Geophysical Union 2000 Fall Meeting, December 15-19, 2000, San Francisco, California. Published: EOS, Transactions, American Geophysical Union, Vol. 81, No. 48, p. F313, November 28, 2000.

Zebker, H.A., P. Segall, S. Jonsson, and F. Amelung, Using the Offset Field to Improve InSAR Measurements: Slip Distribution of the Hector Mine M7.1 Earthquake, Proceedings of the International Geoscience and Remote Sensing Symposium, July 24-28, 2000, Honolulu, Hawaii.

Yun, S-H., J. Ji, and H. Zebker, TOPSAR DEM Interpolation Using a Prediction Error Filter and SRTM DEMs, submitted to IGARSS-2004, Fairbanks, AK, Sept. 2004.

TOPSAR DEM Interpolation Using a Prediction Error Filter and SRTM DEM

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Abstract—We present a method for correcting large-scale artifacts and for interpolating regions of missing data in TOPSAR DEMs. Artifacts are eliminated by subtracting the difference between the TOPSAR DEM and the SRTM DEM. The inversion method using a prediction error (PE) filter was used to interpolate the missing data holes so that the interpolated regions would have the same spectral content as the originally valid regions of the TOPSAR DEM. Along with the PE filter, the SRTM DEM for the same area is used as another constraint in the interpolation. We used cross-validation to obtain the optimal weighting of the PE filter and SRTM DEM constraints.

TABLE I
TOPSAR MISSION VS. SRTM MISSION

Mission	TOPSAR	SRTM
Platform	DC-8 aircraft	Space shuttle
Nominal altitude	9 km	233 km
Swath width	10 km	225 km
Baseline	2.583 m	60 m
DEM resolution	10 m	90 m
DEM coord. system	none	Lat/Lon

I. INTRODUCTION

The recent SRTM mission produced worldwide topographic data at 90m postings. For many analyses, however, finer-scale elevation data are required. We are currently modeling volcanic processes in the Galapagos Islands, and in fact have a 10m-posting DEM of Isabela and Fernandina acquired by the TOPSAR airborne instrument. TOPSAR DEMs are produced from cross-track interferometric data acquired with NASA's AIRSAR system mounted on a DC-8 aircraft. Although the TOPSAR DEMs have a higher resolution than other existing data, they sometimes suffer from missing data holes and other artifacts due to layover (Fig. 2a), flight planning limitations, and roll of the aircraft (Fig. 1). Fortunately, the SRTM DEM has fewer missing data than the TOPSAR DEM, and thus the former provides some information on the missing regions of the latter.

TOPSAR and SRTM missions are the primary sources for DEMs derived from single-pass interferometric data. However, differences in their system parameters such as altitude and swath width (Table I) have resulted in slightly different products. In particular, TOPSAR DEMs have better resolution, while SRTM DEMs have better data coverage and consistency. In this presentation, we describe a method for combining the two DEMs to produce a new DEM that has a resolution of TOPSAR DEM and a consistency of SRTM DEM.

II. METHOD

A. TOPSAR DEM Registration

The original TOPSAR DEM was not registered to a geo-referenced frame. Thus, we registered the TOPSAR DEM to the SRTM DEM, which was registered in a latitude/longitude coordinate system. This registration was done with one affine matrix and one translation vector. We picked 10 tie points from each DEM and solved for the six unknowns – four from the affine matrix and two from the translation vector in a least-squares sense. Then we resampled the TOPSAR DEM such that the resulting DEM would have a pixel spacing exactly nine times smaller than the pixel spacing of the SRTM DEM. Cross-correlation was used to check the remaining offset.

B. Artifact Elimination

An artifact most likely due to roll of the DC-8 aircraft was found in the TOPSAR DEM (Fig. 1). We averaged the TOPSAR DEM by taking 9 looks in both east and north directions and subtract it from the SRTM DEM. With the maximum amplitude of over 20 meters, this artifact would result in substantial errors in many analyses. For example, if this DEM is used for DInSAR application with an ERS2 data pair that has a perpendicular baseline of about 400 meters, the resulting interferogram would contain one fringe of spurious deformation. The space shuttle data does not exhibit significant roll artifacts as its swath is much larger than that of TOPSAR (Table I). Thus, the roll artifact can be eliminated

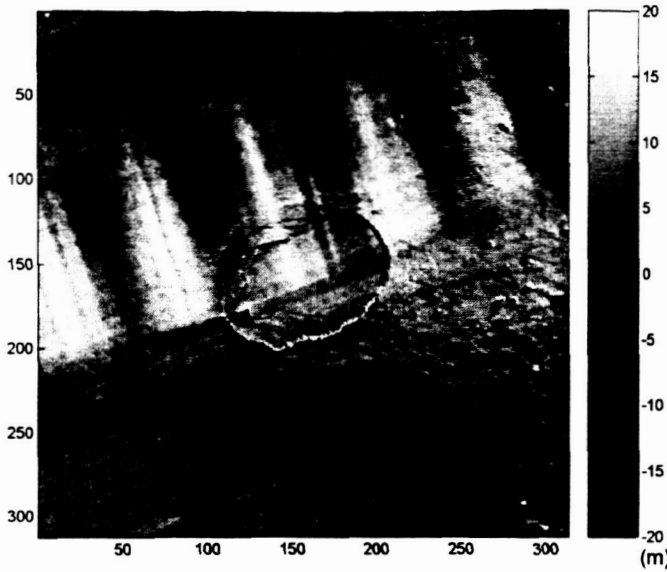


Fig. 1. Artifact due to rolling of the aircraft during the TOPSAR mission. The grayscale is in meters

by subtracting the difference between the TOPSAR DEM and the SRTM DEM.

C. Prediction Error Filter

Based on an assumption that the regions missing data have the same spectral content as the regions with valid data, we generate a PE filter [1] such that it would nullify the valid regions of the TOPSAR DEM. Given this PE filter, we solved for the missing regions such that the interpolated region would also be nullified by the PE filter.

The PE filter, F_{PE} , is generated such that it minimizes the following objective function,

$$\|F_{PE} \mathbf{x}_{existing} - \mathbf{0}\|^2 \quad (1)$$

where $\mathbf{x}_{existing}$ is the valid data from the TOPSAR DEM, and $\mathbf{0}$ is a null vector that has the size of $\mathbf{x}_{existing}$. These matrix and vector expressions are used just to indicate their linear relationship. All inverse problems in this study were solved with conjugate gradient method, where forward and adjoint functional operators are used instead of the explicit form of matrices. Otherwise $M \times N$ times larger memory would be required to store the matrix, where $M \times N$ is the size of the image. The output of each operator becomes an input parameter of a conjugate gradient solver at each iteration.

D. Interpolation

Originally, the SRTM mission produced topographic data at 30m postings (1 arc second). However, those data sets outside of the United States are not available to the public yet. Instead, DEMs at 90m postings (3 arc second) are available to download. These data were produced by taking 3 looks in both east and north directions. In a similar way, we start with the assumption that the pixel value in an SRTM DEM with 90m

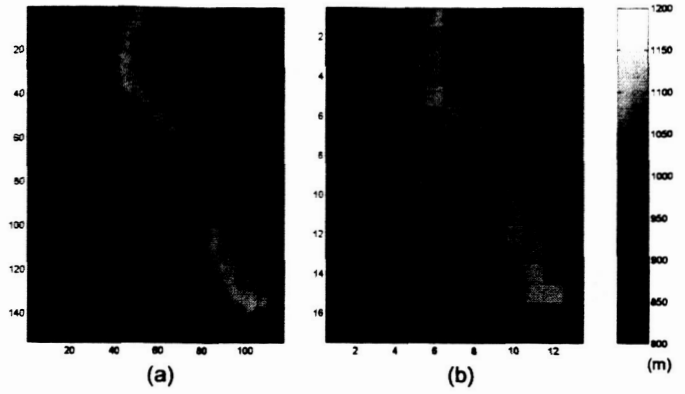


Fig. 2. Example images of (a) TOPSAR DEM, and (b) SRTM DEM of the same area. The grayscale is in meters

postings is equivalent to the average value of a 9 by 9 pixel window centered at the same location in the TOPSAR DEM. We introduce this averaging process in our inverse problem with the hope that we will be able to counteract the averaging process to some degree. With the previously generated PE filter, we next solved for the data missing region, $\mathbf{x}_{missing}$ that minimizes the following two objective functions,

$$\mu_1^2 \|\mathbf{F}_{PE} \mathbf{x}_{missing} - \mathbf{0}\|^2 + \mu_2^2 \|\mathbf{A} \mathbf{x}_{missing} - \mathbf{y}\|^2 \quad (2)$$

where \mathbf{A} is an averaging operator that takes 9 looks, and \mathbf{y} is an SRTM DEM that covers the missing regions of the TOPSAR DEM. Here the $\mathbf{x}_{missing}$ actually has the dimensions of the TOPSAR DEM, while the \mathbf{y} has the dimensions of the SRTM DEM. Examples of $\mathbf{x}_{existing}$ and \mathbf{y} are shown in Fig. 2a and Fig. 2b respectively. The μ_1 and μ_2 are weights for the two objective functions.

III. RESULTS

The cross-validation technique [2] was used to determine the optimal weights (Fig. 3) of the two objective functions in (2). Since the interpolated region tends to have the same spectral content, it is crucial to select a proper window that will be used to generate the PE filter. Unless the selected window represents the true spectral content of the regions with data missing, it is not a good idea to rely heavily on the PE filter. Thus, we tried to fit the SRTM DEM as much as possible, allowing minimal effect from the PE filter. This can be achieved by implementing cross-validation only for the second objective function in (2).

In the case of the example shown in Fig. 2, the minimum cross-validation sum of squares (CVSS) was obtained when $\mu_1 = 0.16$ and $\mu_2 = 1$. Even though only the second objective function was used to calculate the CVSS, the minimum did not occur at $\mu_1 = 0$, because the averaging operator alone could not predict the missing data in an adjacent pixel. Fig. 4 shows the interpolation results applied on Fig. 2, with the optimal weighting (b) and two extreme cases (a,c). The same method was applied to the entire crater of Sierra Negra

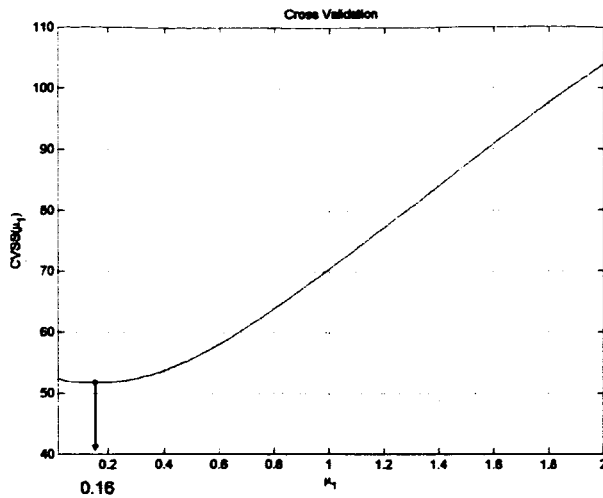


Fig. 3. Cross-validation sum of squares, ($\lambda_2 = 1$)

volcano at Galapagos Islands (Fig. 5).

IV. CONCLUSION

The roll artifact of the aircraft was found to dominate in the difference image between the TOPSAR and SRTM topographic data. This error can be eliminated by subtracting the difference from the TOPSAR DEM. Solving the inverse problem constrained with a PE filter and SRTM DEM information provided high-quality interpolation results. The cross-validation seems to be a proper choice for finding the optimal weighting in the inversion. This makes the interpolation less biased and guarantees the best fitting to the SRTM DEM. The quality of many other TOPSAR DEMs can be improved in a similar way.

ACKNOWLEDGMENT

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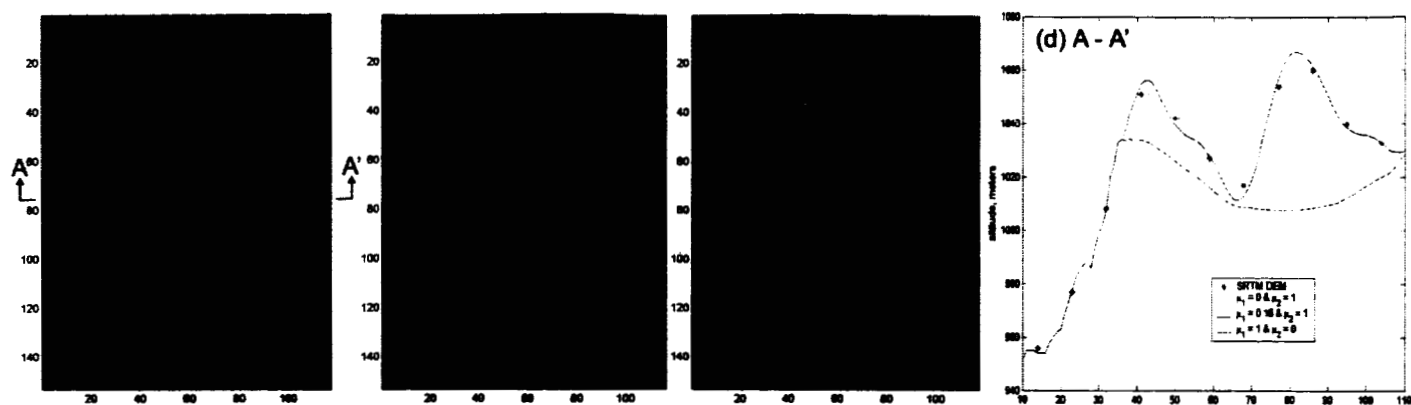


Fig. 4. Interpolated TOPSAR DEM with weights combination of (a) $\mu_1 = 1$, $\mu_2 = 0$, (b) $\mu_1 = 0.16$, $\mu_2 = 1$, and (c) $\mu_1 = 0$, $\mu_2 = 1$. Cross-sections along A-A' in (a) are shown in (d).

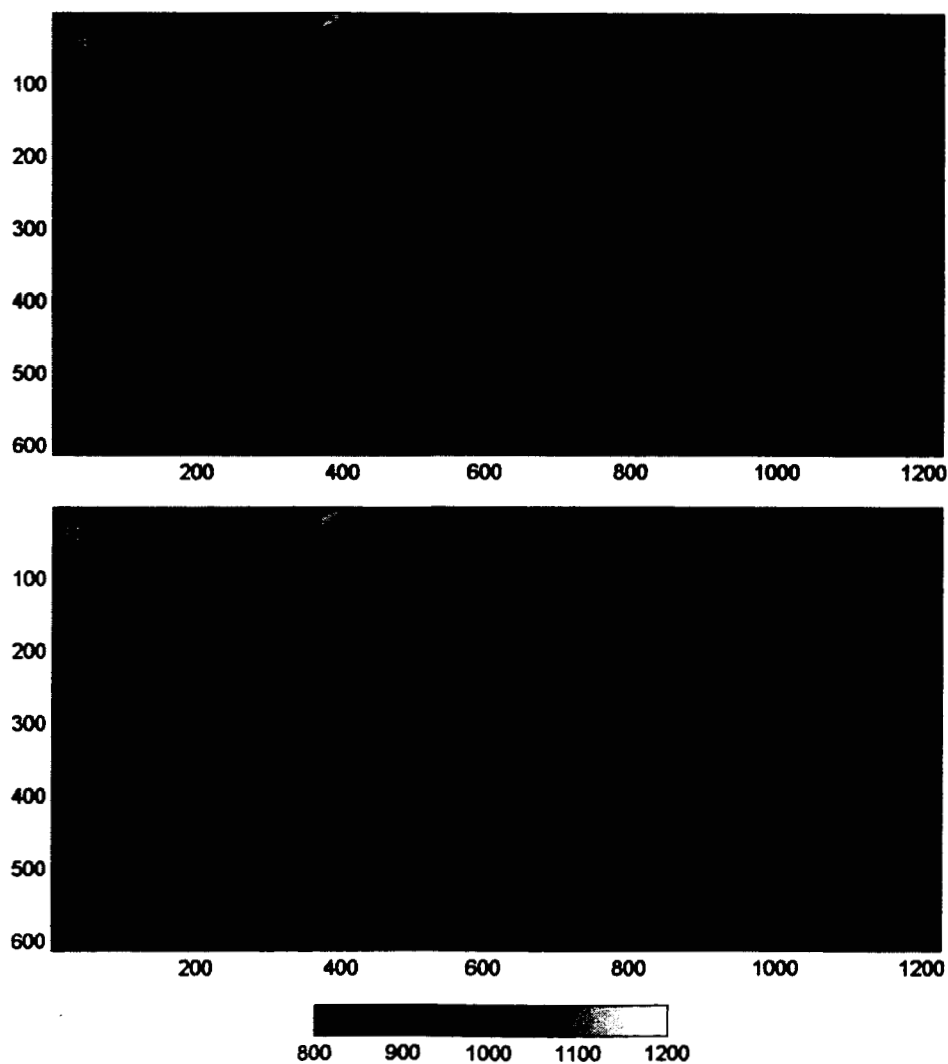


Fig. 5. The original TOPSAR DEM (a) and the reconstructed DEM of the same area after interpolation with PE filter and SRTM DEM constraints (b). The grayscale is in meters, and the scale is about 12 km across the image.